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Morphometry and Hydrology of the Four Large Lakes of Sweden

The four largest Swedish lakes Vänern, Vättern, Mälaren and Hjälmaren all have a tectonic origin with multidirectional fault fissures, which influence the topography of the bottoms and the creation of subbasins. All the four lakes have been subject to several glacials, the latest of which started to recede from central Sweden c. 10 000 years ago. The many differences between the four lakes can be explained by their shapes, sizes and the relation between the sizes of the drainage basins and the size of the lakes. This paper focuses on processes considered relevant to aquatic organisms of the lakes: water balance, water residence time, water temperature, water exchange between subbasins within the lakes, and other internal water movements. Links between pollution, water exchange and retention of nutrients are discussed with an example from Lake Vänern.

INTRODUCTION

Sweden is fortunate to have a great number of fairly large lakes. There are 395 lakes with a surface area exceeding 10 km^2 within the country (1). The four largest lakes, L. Vänern, L. Vättern, L. Mälaren and L. Hjälmaren, all situated in central Sweden, have a total surface area of 9086 km^2, which constitutes 21.6% of the total lake area of Sweden. The drainage area of these four lakes amounts to 79 845 km^2, which is c. 18% of the total area of Sweden. In a global perspective, L. Vänern is ranked as 29 and L. Vättern as 42 based on lake volumes. L. Mälaren and L. Hjälmaren, where the latter constitutes a part of the drainage area of L. Mälaren, are smaller and do not belong to the 50 largest lakes in the world (2).

All lakes have been shaped and reshaped by several glacials that have covered Scandinavia and parts of northern Europe during the past 3 million years. The latest glacial began retreating from central Sweden c. 10 000 yrs ago. The lakes provide an exceptional freshwater supply and support abundant fish communities. Their attractive sceneries and closeness to populated areas also make them important recreational resorts. When comparing the lakes, however, it is remarkable how fundamentally different they are in most respects. The range of processes that regulate the hydrology of the lakes is very broad. This can be explained by variations in morphometry and differences in the ratios between the lake area and drainage area as well as the size of the lake itself.

Indeed, the only things they seem to have in common are their large size in relation to other Swedish lakes and their position within the temperate zone, which make them subject to a similar climate.

Here an attempt is made to describe the structural circumstances and hydrological processes that have been identified, and to elucidate the differences. The links between water exchange and chemical response are discussed with an example from L. Vänern. The sediments have not been treated in this paper but it must be emphasized that the exchange between sediment and water is important. A number of investigations of bottom dynamics and sediment concentrations, mainly of metals, have been published by Håkanson (3–6). Furthermore, Håkanson studied

Figure 1. The four largest lakes of Sweden and their watersheds. For lakes Vänern and Vättern basin borders (red lines), main inlets and outlets, and sampling sites are given.

lake-basin morphology, sedimentology and the theory behind sediment dynamics.

MORPHOMETRIC FEATURES

The most striking features of the lakes are their shapes (Fig. 1). Vänern, Mälaren and Hjälmaren all have morphometric constrictions, which more or less separate subbasins from each other, leading to variations in water quality between different subbasins of the same lake. L. Vättern forms an exception because it constitutes only one basin. Furthermore, the lakes differ in their abundance of islands. L. Vänern has several groups of islands located in various parts of the lake. L. Vättern has all its islands but one, Visingsö, concentrated as an archipelago in its northern part. L. Mälaren is yet again different, having a lot of large islands that almost fill the subbasins entirely (Fig. 2). Indeed, L. Mälaren could be considered as one big archipelago containing both large islands and small islets.

L. Vättern was created by a series of vigorous movements in the earth's crust. The large east-west fault, through the present outlet of the lake, first appeared 200–400 million years ago. Around 40–50 million years ago, the region around today's southernmost part of the lake was subject to great tensions that stretched the earth's surface in an east-west direction. As a result of these forces the surface cracked, whereupon the fault that constitutes L. Vättern was created. A fault precipice on the eastern side of L. Vättern was produced at this time.

A north-south zone of faults divide L. Vänern into 2 separate subbasins, Värmlandssjön and Dalbosjön. They are separated by a shallow archipelago area. The lake bottom topography is generally very rough. A very conspicuous marginal moraine transverses the lake at the southernmost end and gives rise to 2 pointed capes facing each other. They form a topographical barrier between the outlet bay and the central parts of Dalbosjön (Fig. 1). L. Vänern has many archipelagoes, which in some cases receive water from tributary rivers. The degree of constriction, water turnover and differences in water flow and water quality of the tributaries, produce great variation in dynamic patterns.

The complicated structure of L. Mälaren was created by faults consisting of several fissures orientated in a north-south direction. The division into several subbasins is caused partly by tectonics and partly as a result of glacials which produced moraine structures, such as eskars that transversed the lake.

The predominant features of the morphometry of L. Hjälmaren are faults and ridges. Three noticeable fault zones, mainly running in an east-west direction, can be identified in the southern parts of the lake. The northern parts are shallower and dominated by islands, capes and bays. Several eskars cross L. Hjälmaren from north to south. The ridges and faults divide the lake into 5 rather distinct subbasins, named (from west to east): Hemfjärden,

Figure 2. The subbasins of L. Mälaren and Hjälmaren. Main inlets and outlets and dicussed sampling sites are given.

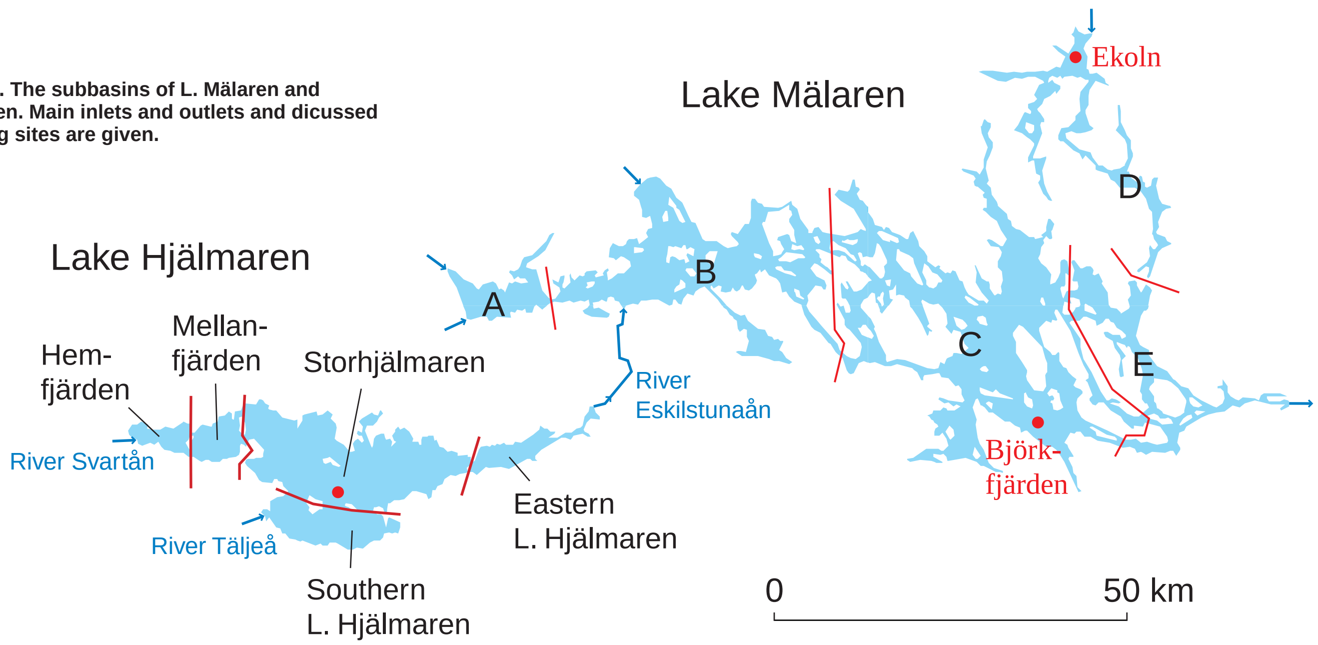

Table 1. Morphometric data on Vänern, Vättern, Mälaren and Hjälmaren. Data sources: Vänern (4), Vättern (3), Mälaren (7) and Hjälmaren (8).

	L. Vänern	L. Vättern	L. Mälaren	L. Hjälmaren
Water volume, km^3	153	74	14.0	3
Surface area*, (a) km^2	5648	1856	1096	484
Drainage area**, (A) km^2	46 830	6359	22 603	4053
Ratio a/A	0.12	0.29	0.05	0.12
Maximum depth, m	106	128	63	22
Mean depth, m	27	39.8	12.8	6.1
Shore length development, km	1943	460	960	290
Lake area/shore length ratio, km	2.9	4.0	1.1	1.7
Number of islands > 0.01 km^2	813	87	397	99
% island area	4.1	2.2	32.2	3.1
Number of subbasins	2	0	5	5

* islands excluded
** including lake area

Table 2. Annual water balance for the Swedish large lakes expressed in mm yr^{-1}. Data sources: Vänern (9), Vättern (3), Mälaren (8) and Hjälmaren (10).

Time period	L. Vänern 1931–1960	L. Vättern 1941–1970	L. Mälaren 1965–1998	L. Hjälmaren 1966–1984
Input	2679	612	4872	1746
Precipitation	631	510	533	502
Lake evaporation	541	442	470	502
Output	2768	680	4934	1746

Mellanfjärden, Storhjälmaren, Eastern Lake Hjälmaren and Southern Lake Hjälmaren (Fig. 2).

WATER BALANCE

The water balance for the lakes summarizes all imports and exports of water to the individual lakes (Table 2). The precipitation is around 500 mm yr^{-1} (500–630 mm yr^{-1}), with the higher values in the western drainage basins. The annual evaporation from all four lakes is in the range of 500 mm yr^{-1} (470–570 mm yr^{-1}). Precipitation on the lake surface, thus, roughly balances the evaporation. Due to the different size of the drainage areas the water throughflow in the lakes varies by more than one order of magnitude (Table 2). It is noticeable that deposition of, e.g. pollutants on the lake surface will have a stronger effect on a lake with a large proportion of direct precipitation than one with a small proportion since most often airborne pollutants show high retention in the watersheds. L. Mälaren is thus least affected by precipitation over its surface, as precipitation only accounts for 10% of the total water inflow to the lake. At the other extreme, on-lake precipitation has a greater impact on L. Vättern, which receives 45% of the water that has not passed through soil. Such a lake is very sensitive to the composition of the precipitation.

EXTERNAL WATER EXCHANGE

The tributaries to the lakes have various hydrological regimes. Those discharging into L. Vänern and L. Mälaren in particular, are situated in a border zone between a northern snow regime, with low winter- and high spring snowmelt runoff, and a mixed snow- and rain regime with higher winter runoff. This means that the inflow throughout the year varies between lakes, but also between different parts of the same lake. The interannual variation may also be large.

More than one third (c. 35%) of Lake Vänern's water inflow is provided by the river Klarälven, which has a typically northern snow regime (11). In total, 80% of inflowing water is derived from regions with a northern snow regime. All major watercourses with this regime are however regulated, leading to a levelling out of the variation over the year. The watercourses feeding the southern parts of the lake have a more irregular flow, and have larger interannual variation than the northern inflows.

L. Mälaren's main drainage basins are located to the north and west of the lake (Fig. 1). These regions are characterized by the northern snow regime. In the southern and eastern parts of the lake and its surroundings, the hydrological regime is quite variable, and winters may either be anything from snow-free to having a long-lasting snow cover.

Due to the storage properties of Lake Hjälmaren the water runs without large flow variations through the river Eskilstunaån into L. Mälaren. Two watercourses, the rivers Svartån and Täljeå, together provide 64% of the water inflow into L. Hjälmaren and both drain regions with a mixed snow-rain regime. They enter the lake in its westernmost and southern basin, respectively (Fig. 2).

L. Vättern has a small watershed in comparison to the surface area of the lake. The drainage area looks like a rather thin lining around the lake. A number of unregulated, minor watercourses, the largest of which is the river Forsviksån, feed L. Vättern and all have a mixed hydrological regime (Fig. 2).

All lakes are influenced by the above variation in water-flow regimes in such a way that both the inflow and the outflow of, e.g. nutrients, are unevenly distributed throughout the year. In some cases, this has a crucial impact on the supply and consumption of nutrients, as biological processes are governed mainly by the access to nutrients and light.

The fate of substances in lakes is also strongly dependent on the water residence time in the lake basins, here defined as the volume of the lake divided by the total water input to the lake (Table 3).

Lakes with short residence times are also very sensitive to interannual flow fluctuations, because a large portion of the water in those lakes is exchanged during a year. In this respect, the four large lakes discussed here display extreme differences. For L. Vättern, with its large water volume and comparatively small water inflow, seasonal variations in the tributary watercourses have very little impact on the lake's water quality. In contrast, Mälaren and Hjälmaren are strongly affected by the annual peaks in water inflow and the associated input of substances, that have an impact on the biological production in the lakes.

Large lakes often have long water residence times as compared to small lakes. Whereas the residence time for the four largest Swedish lakes spans between 2.8 and 58 yrs (Table 3) the median residence time for 1570 common Swedish forest lakes (0.01–95 km^2) is calculated to be 0.7 yrs (12). The residence time of water in L. Vättern is extremely long, which is also verified by a comparison with the two largest European lakes Ladoga and Onega, which both have residence times of 12 yrs (13). The Laurentian Great Lakes have water residence times varying between 2.6 and 190 yrs. However, some subbasins or bays with confined archipelagoes that border the Swedish large lakes have much shorter residence times than the entire lakes.

LAKE INTERNAL WATER EXCHANGE

Water residence times in subbasins within a lake are generally shorter than for the entire lake, and as a result retention of all nonconservative substances is affected.

Nonconservative substances, such as phosphorus, nitrogen or-

Table 3. Hydrological data on Vänern, Vättern, Mälaren and Hjälmaren (4).

	L. Vänern	L. Vättern	L. Mälaren	L. Hjälmaren
Mean outlet discharge, $m^3 s^{-1}$	496	42	168	27
Mean surface runoff L s^{-1} km^{-2}	11.6	6.6	7.4	6.6
Residence time, years	9.8	58	2.8	3.7
Water level amplitude, m	1.7	0.28	0.95	0.6
Upper m a. s. l.	44.85	88.58	1.11*	22.22
Lower m a. s. l.	43.16	88.30	0.16*	21.62

* ref. (14)

Table 4. Water flow and residence time of water as well as phosphorus and nitrogen retention in the different subbasins of L. Mälaren. Data sources: phosphorus retention (15), nitrogen retention (16).

Basin	A	B	C	D	E	L. Mälaren
Outflow ($m^3 s^{-1}$)	89	132	144	26	172	172
Residence time (year)	0.07	0.6	1.9	1.3	0.3	2.6
Phosphorus retention (% of total input)	7	29	52	45	27	70
Nitrogen retention (% of total input)	5	24	42	31	23	56

ganic matter, etc., brought into the lakes are affected by time-dependent degradation or by sedimentation processes which will proceed roughly proportional to the water residence time of the lake itself, and also to the residence times within different subbasins of the lake.

An example from L. Mälaren can illustrate how varying water residence times in the subbasins of the lake (Fig. 2) influence the phosphorus and nitrogen retention.

Both the residence times and nutrient retentions in the subbasins are smaller than those of the entire lake (Table 4). There is a highly significant linear positive correlation between the water residence time and nutrient retention, $R^2 = 0.94$ for phosphorus retention and 0.93 for nitrogen retention.

Water exchange or "ventilation" between coastal areas and major open basins are also important in the discussion on the role of coastal archipelagoes or bays as "nutrient filters" meaning their local nearshore retention. Methods to estimate water residence times for different semi-isolated archipelagoes or embayments have been developed and applied to some archipelagoes bordering L. Vänern (17). The "salt dilution method" (18) has been rather successful as a way of determining the water exchange in L. Vänern (19).

The salinity of many tributaries deviates from that of the receiving waterbody, which often results in a salinity gradient around the mouth of the tributary in bays or archipelagoes. The difference in water salinity between such an archipelago area, and the lake beyond is a measure of the water-exchange properties of the lake. These can be calculated from a mixing equation between river-water salinity and that of the main body of the lake.

Another method of measuring water exchange is based on the hypothesis that a large part of the water exchange in a semi-enclosed nearshore area can be explained by the morphometry of that area. The model developed (20) was successful in explaining the exchange time of the surface water, using morphometric data such as the size and shape of the studied area summarized as an index of topographic openness (Fig. 3).

The 2 methods described above have both been applied in various archipelagean regions of L. Vänern, e.g. in studies of the mouth of Klarälven (Table 5).

The morphometric approach was based on a function describing water residence time as a function of topographic openness (Fig. 3). As can be seen from the Table the methods give estimates of the same magnitude but with some divergencies. The morphometric approach tends to give more rapid turnover time than the salt dilution method, which is explained by the fact that the morphometric approach only takes surface water into account. By the use of these water residence times applied to an empirical phosphorus retention model (21), a phosphorus retention of 15–22% was calculated for these nearshore areas as compared to estimates of 70% phosphorus retention for L. Vänern as a whole (22).

HYDRODYNAMICS

Within-basinwater movements are created by various processes that may act singly or in combination, and be occasional or act with long duration. They may be divided into 4 groups:

i) river inflows;
ii) convective currents;
iii) wind-induced currents (direct and indirect *via* surface seiches, etc.);
iv) internal seiches.

Local water inflow: i) This inflow from watercourses feeding a coastal area causes outward water movement. River flow may also block counter flow of coastal water if the river mouth is situated in a semienclosed area and the flow is high. If the entering water has a deviating density, (salinity or temperature dependent) currents are induced. Such currents are basically a nearshore or archipelago phenomenon important for water exchange between archipelagoes or bays and the offshore regions.

Convection: ii) The cooling of surface water, gives rise to currents when the water sinks due to increased density. Such mixing is a lakewide phenomenon. Through autumn convection the thermocline weakens and sinks. Autumnal strong winds enhance the destabilization, which ultimately leads to the breakdown of temperature stratification. However, temperature changes occur faster in shallow areas than in neighboring deep areas. The density difference between warm and cool water, therefore, also causes a water exchange between the archipelagean region and the main water mass.

Wind interactions: iii) With the water surface these interactions give rise to an array of water movements. Several of these are confined only to large lakes or become important only in such lakes.

Lakes with large open areas are more exposed to wind than small lakes. A larger wind fetch supplies more energy to the water mass and causes a more efficient mixing of epilimnion and a deeper thermocline than in smaller lakes. Temporal wind variations produce complex patterns of currents with oscillations and countercurrents. When winds act upon the surface of a lake, the surface becomes tilted as the water level rises towards the windward shore and sinks on the lee side. In a stratified lake, the water masses are shuffled too, and the warm surface water gathers on the windward side and the colder water on the lee side, causing the thermocline to become tilted. An alteration of the wind, whether a cessation or a change of direction, causes the body of

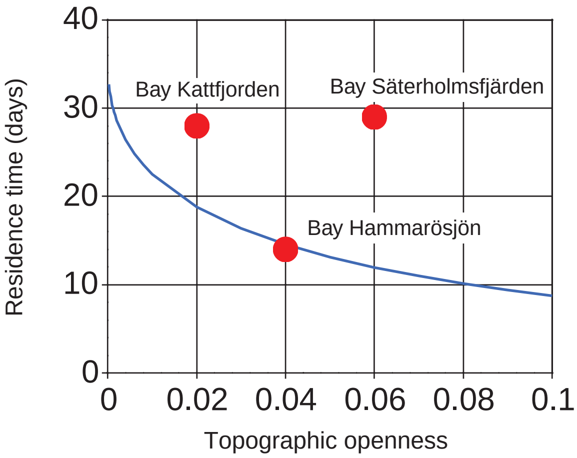

Figure 3 Water residence time of surface water as a function of topographic openness. The function is derived for embayments or archipelagoes along the Swedish coast (20). Residence times calculated by the salt dilution method for 3 bays in Vänern (see text) indicated for comparison.

Table 5. Residence time (days) of water in 3 effluent areas of the river Klarälven estimated in 2 cases by the salt dilution method (17, 19) and in addition by a morphometric approach Wallin and Persson (17).

	Salt dilution 1 (17)	Salt dilution 2 (19)	Morphometric approach (17)
Bay Kattfjorden	–	28	19
Bay Hammarösjön	8	14	14
Bay Sätersholmsfjärden	16	29	12

water to start resuming its equilibrium, thereby inducing oscillating movements, known as seiches. The seiches arise both at the surface, as surface seiches, and in the thermocline, internal seiches, which are discussed below. Surface seiche periodicity depends on the shape of the basin and the thermal stratification. The theory behind calculations of the periodicity of seiches was formulated at the turn of the 19^{th} century (23). The uninodal surface seiche of L. Vättern has a periodicity of 179 min and a maximum amplitude of 12–13 cm (24).

In large, Northern Hemisphere lakes, e.g. L. Ontario (25) and L. Vänern (26, 27), winds and global rotation create a cyclonic circulation that gives the thermocline a calotte-like shape. Different methods of estimating the cyclonic circulation of L. Vänern have produced similar results. The methods used are the dynamic height method based on measurements of temperatures (27, 28), and mathematical modelling of currents (29). The estimated pattern of circulation (Fig. 4) has been verified by measurements of currents. For L. Vättern neither simulations nor observations have been able to prove the occurrence of cyclonic circulation (30). Cyclonic circulation is not expected to occur in L. Mälaren and L. Hjälmaren where the basin topography probably is too irregular, and their littoral zones too long in comparison to their areas.

Internal seiches: iv) The tilting of the thermocline in response to an altered wind stress, causes large movements of water. In L. Vättern, seiche-like movements of the thermocline at the ends of the lake (Fig. 1) may move upward or downward more than 15 m within a few days and considerable amounts of water are displaced. In large lakes, the global rotation causes the internal seiche to take the form of a rotating wave (Kelvin wave). In the Northern Hemisphere, this wave turns anticlockwise with the same periodicity as the internal seiche. The rotating wave is affected by the topography of the shore and of the bottom of the lake. Therefore, these waves are also known as topographic waves. In regions close to the shore the currents are amplified and become parallel to the shore. The effect on the shore zone is determined by the wave-phase speed of the internal seiche and the Coriolis factor, which in itself depends on latitude. These currents are known as "coastal jets" and have been observed in Värmlandssjön basin (Fig. 1) of L. Vänern (28). Wave motions similar to Kelvin waves have been detected in L. Vättern by observations of vertical temperature profiles and continuous measurement of currents. The periodicity has been estimated to be c. 136 hrs and the phase speed c. 0.5 m s^{-1} (30).

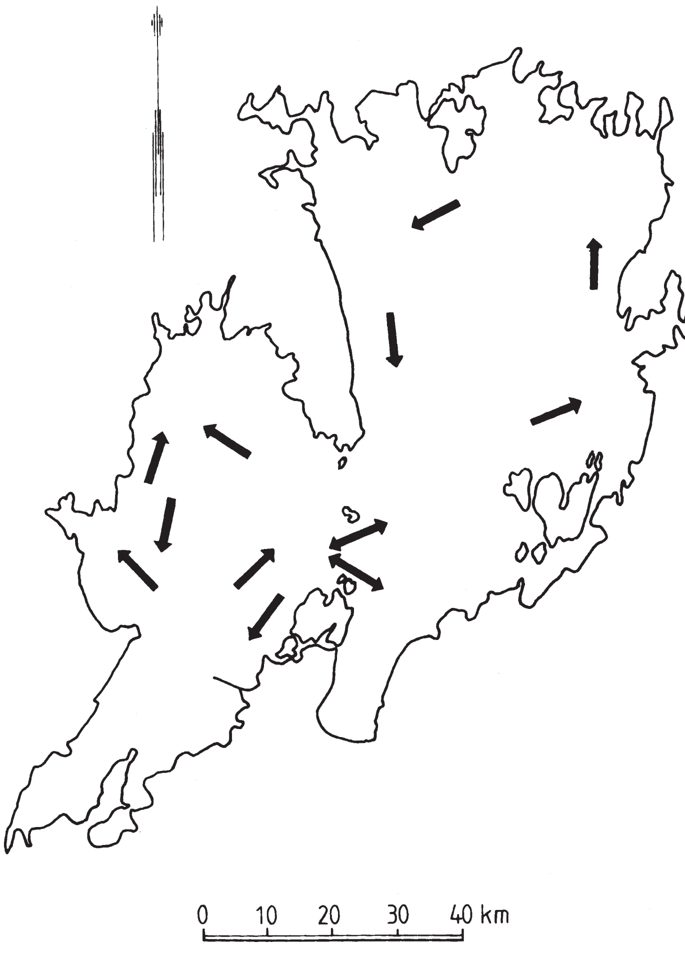

Figure 4. Dominating current directions in August 1971 and 1972 in Vänern according to measurements performed with automatic recording equipment (26).

THERMODYNAMICS

Heating and cooling processes as well as the resulting lake temperatures depend on basin size and form in combination with meteorological conditions, and is best brought forward by considering the different seasons separately.

Winter

The temperature of the large lakes sinks below 4°C in the winter. The dissimilarities in sizes and shapes are responsible for temperature variations, both within and between the different lakes. Large, deep lakes have a greater capacity for storing heat than small lakes. As a consequence the cooling process of large lakes is slower than that of small lakes which influences the winter freeze-up.

Presence of ice affects the temperature, circulation and light levels, all of which influence the biota of the lakes. L. Mälaren and L. Hjälmaren freeze virtually every year with occasional deviations, whereas L. Vänern and L. Vättern rarely do so, except in areas close to the coast and in archipelagoes. Lakes not covered with ice are subject to an overall equalization of water temperature and chemical properties, both caused by wind-generated turbulence and convection. The water in ice-covered lakes develops a vertical temperature stratification with warmer water (≈ 4°C) at the bottom and cooler at the surface, a pattern which is reinforced during the winter due to emission of heat from the sediments. The vertical mixing of water under such conditions is very slow, leading to a chemical stratification. In some parts of L. Mälaren, this pattern leads to an oxygen deficiency in the bottom layers, caused by decomposition of organic matter. A study of the Åsfjorden Bay in the 1970s, a heavily polluted bay in L. Vänern, showed that serious oxygen deficiency only occurred during winters when the Bay was covered with ice.

When considering a future situation, including the possibility of global warming (31), alterations in freezing and ice conditions must be taken into account, especially for lakes that lie in the border zone of freezing or only freeze partially. The four large lakes belong to this category.

Spring

Spring can be defined as the warming-up period, starting when the water temperature of the lake exceeds the density maximum at 4°C and ending when a thermocline has developed throughout the lake. A temperature increase occurs at the surface, and winds then promote the mixing of heated water with underlying layers. Initially, there is a vertical mixing of water masses due to low stability of the waterbody. There is frequent breaking-up of the thermocline, due to spells of strong winds and periods of low insolation. As temperature rises also the density differences increase leading to higher stability and thermal stratification.

In the case of large lakes, subject to winter temperatures below 4°C, the increase in water temperatures in the spring causes a phenomenon known as thermal bar. Thermal bar is typical for large open basins and has only been observed in L. Vänern (32). The expression refers to the barrier of 4°C-water, which builds up between the areas close to the shore and the central, open area of the lake (Fig. 5). Between this barrier and the shore the heating proceeds at a steady pace and a thermocline might develop. The water in the central part of the lake warms up more slowly, as a lot more heat energy per surface area is needed before the temperature reaches 4°C. During this phase there is an intense vertical circulation of water, supplying deeper layers with oxygenated surface water. As the heating goes on, the thermal bar moves towards the central part of the lake and disappears when temperatures throughout the waterbody exceed 4°C. The thermal bar isolates the zones close to the shore from the central parts, a situation which influences both pollution patterns and the biological production. The duration of the thermal bar is usually around a month. In even larger lakes, like Lake Ladoga, there is also an additional thermal bar during autumn cooling (13).

Summer

During summer, the thermocline stabilizes and deepens. The process has been investigated using temperature data from all four lakes, and temperature profiles for July exemplify summer conditions (Fig. 6). Complementary data (Table 6) support the description of seasonal thermodynamics. In Figure 7, the median strength and position of the thermocline during May though September is presented.

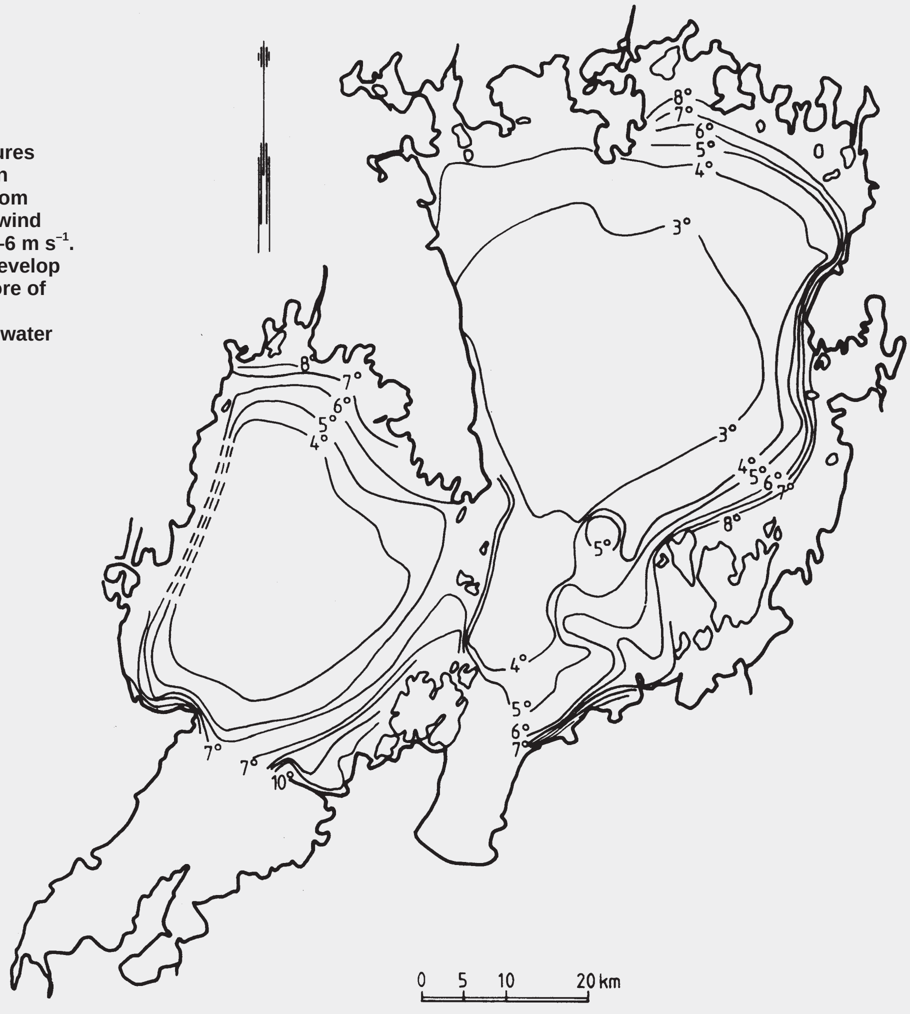

Figure 5. Surface temperatures indicating the thermal bar in Vänern. Satellite imagery from 1971-05-12 (26). Prevailing wind direction SW, windspeed 2–6 m s^{-1}. The thermal bar does not develop along the northwestern shore of Värmlandssjön, as the predominating winds drive water onto the windward side.

Table 6. Thermal conditions in the studied lakes based on temperatures from the regular monitoring program. Thermocline depth and temperatures of the epilimnion are given mid-monthly for June–September. Lake mean depths are included for comparison.

		June		July		August		September	
	Mean depth (m)	Temp (°C)	Depth (m)	Temp (°C)	Depth (m)	Temp (°C)	Depth (m)	Temp (°C)	Depth (m)
L. Vättern	39.8	8.3	17.5	13.2	11.0	11.7	16.0	12.6	–
L. Vänern	27.0	9.8	10.3	15.2	12.3	16.8	15.5	13.3	23.5
L. Mälaren	12.8	13.3	12.5	17.0	10.0	17.8	12.0	14.5	20.0
L. Hjälmaren	6.1	15.8	–	18.6	–	18.7	–	10.6	–

From Table 6 it can be seen that L. Vättern has the lowest epilimnion temperatures of the four lakes. L. Hjälmaren on the other hand has the highest summer temperatures. The reason being that deep lakes have a higher heat storage capacity than shallow lakes. Thus, deep lakes are both heated and cooled down slower than shallow lakes. There is a significant negative correlation between mean depth and epilimnion temperature in June ($R^2 = 0.96$), July ($R^2 = 0.99$), and August ($R^2 = 0.87$). In September when cooling has proceeded, the shallow L. Hjälmaren has cooled much faster than the other lakes, and reached the lowest temperature.

In the deep L. Vättern, the thermocline develops late (June) is weak (no distinct transient) and also breaks early (Fig. 7). The thermocline is much weaker than for instance in L. Ekoln, a subbasin of Mälaren. In the shallow L. Hjälmaren no thermocline

Figure 6. Long-term mean water temperatures in July as a function of depth in Vättern (site Edeskvarnaån NV), Vänern (site Tärnan SSO), Mälaren (sites Ekoln and Björkfjärden), and Hjälmaren (site Storhjälmaren). Data from thermistor measurements. Sampling interval 1–2 m.

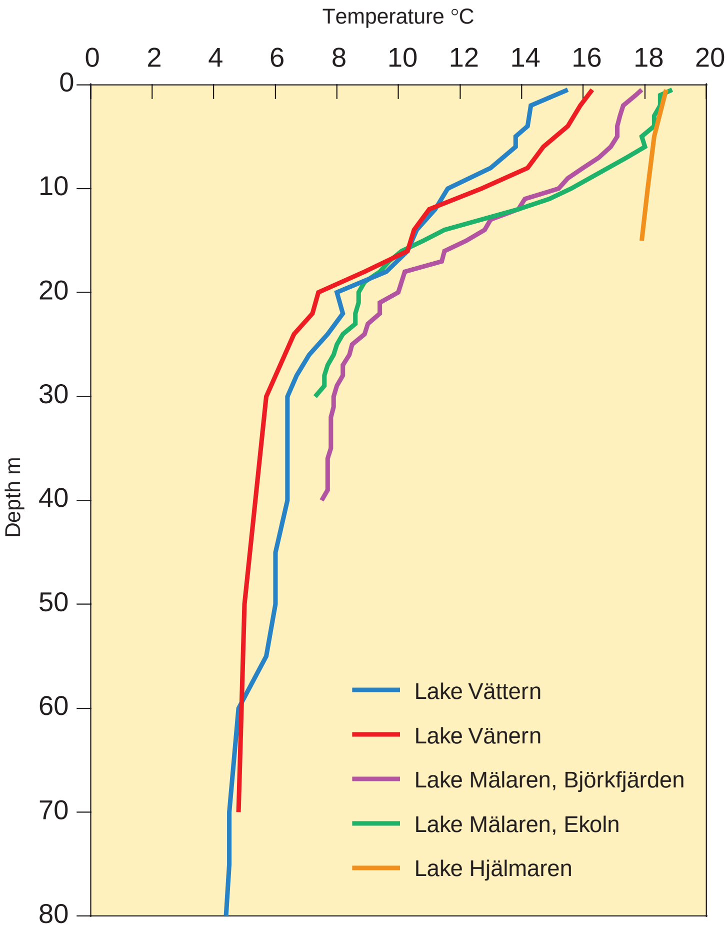

Table 7. Total input of water ($m^3 s^{-1}$) during the summer period (120 days) in relation to water "supplied" from the hypolimnion by the downward propagation of the thermocline (average conditions).

	Lake Vänern	Lake Vättern	Lake Mälaren
Total input (total)	593	66	188
From hypolimnion (hypo)	5300	8300	550
Ratio hypo/total	9	126	3

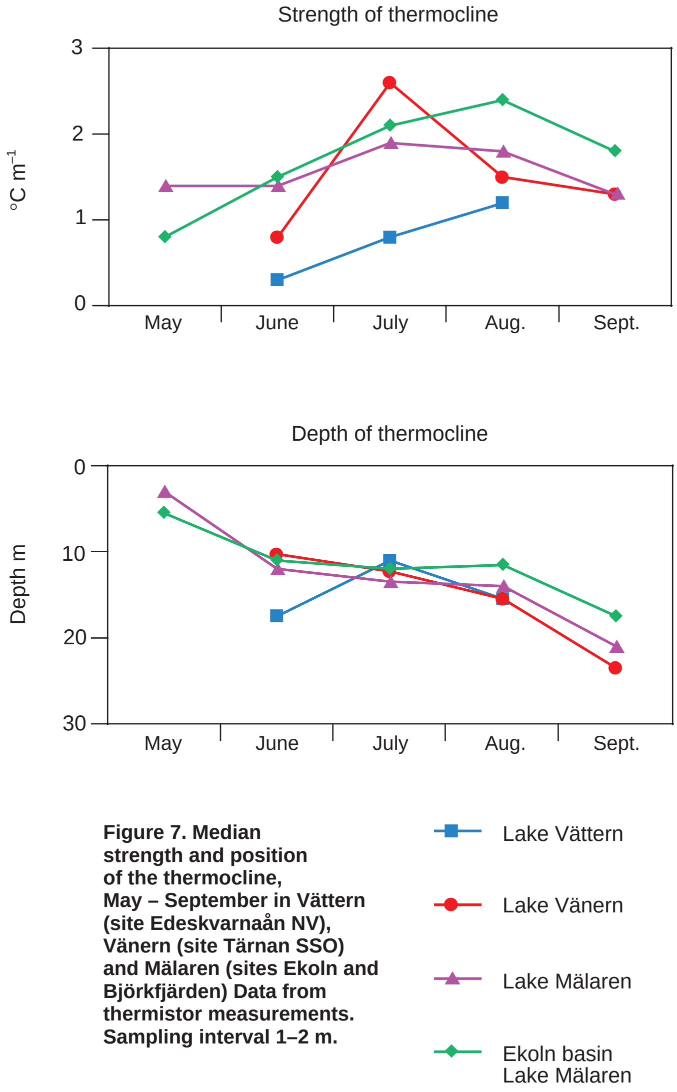

Figure 7. Median strength and position of the thermocline, May – September in Vättern (site Edeskvarnaån NV), Vänern (site Tärnan SSO) and Mälaren (sites Ekoln and Björkfjärden) Data from thermistor measurements. Sampling interval 1–2 m.

develops. In L. Vänern the strength of the thermocline reaches its maximum in July while L. Mälaren and L. Vättern develop their strongest thermocline in August. The lowering of the thermocline (Fig. 7) progresses during summer and reaches its maximum depth in September. The maximum depth of the thermocline varies among the stratified lakes between 17 and 24 m.

The strength of the thermocline is defined as the maximum vertical temperature gradient expressed as °C m^{-1}. It varies in the lakes between 0.3 and 2.6°C m^{-1} (Fig. 7).

The lowering of the thermocline leads to a continuous entrainment of hypolimnion water to the epilimnion, a process which supplies nutrients for the production. From a hydrochemical point of view it is interesting to relate this entrainment to external inflow into the epilimnion from tributary watercourses and precipitation over the lake surface (Table 7). The epilimnion of L. Vänern receives c. 55 km^3 former hypolimnion water in 120 days, a figure equivalent to an external inflow of 5300 m^3 s^{-1}, which is 9 times as much as that supplied by tributaries and precipitation. The corresponding value for L. Mälaren is 3 times as much input from a deepening of the thermocline than from external inflow and for L. Vättern the value is 126 times. From a hydrochemical point of view, L. Mälaren is least affected by a difference in water quality between the hypolimnion and the epilimnion, whereas the surface water of L. Vättern is extremely dependent on the condition of the hypolimnion.

Autumn

The cooling process begins in September and the water temperatures decrease. Downward convection, caused by a cooling of the surface water, destabilizes the body of water. The thermocline weakens and sinks. The destabilization is further reinforced by the increased frequency of strong winds occurring in the autumn. At the end of September or beginning of October the vertical mixing of water is complete and remains so until the lake eventually freezes. As with most thermic processes basin size and depth are instrumental for the pace of the cooling process leading to the different timing of stratification break-up (Table 6).

CONCLUSIONS

Lake Vänern is large enough to enable the occurrence of cyclonic circulation. It also allows internal waves, described as Kelvin waves. A thermal bar, which temporarily separates nearshore water from the more central waterbody, develops during the spring. The residence time is long, but even so the precipitation over the surface of the lake affects the chemical properties of the lake to a comparatively small degree. Lake response to changes in the pollution load is slow. The archipelagean regions of L. Vänern often serve as traps for incoming material, through tributaries or from other sources.

Lake Vättern is an elongated and deep tectonic lake with few islands. It has few constrictions and a very slow water turnover rate. Deposition onto the surface of the lake has a large impact on the water quality of the lake. In a short-term perspective, changes in internal processes have a larger impact on lake status than alterations in external supply. Internal seiches occur, but in contrast to the situation in L. Vänern, no cyclonic circulation has been observed.

Lake Mälaren is very different from both L. Vänern and L. Vättern in that it consists mainly of an archipelago with numerous islands. However, it is easy to identify subbasins within the lake. The water residence time of L. Mälaren is relatively short, giving a fast response to changes in input water quality. The different water quality of tributaries and the complex pattern of subbasins and the residence times cause considerable variation in water quality. The lake is too small to give rise to internal rotating waves.

Lake Hjälmaren is a shallow lake divided into a number of more or less distinguishable subbasins. Due to the shallow basin no summer temperature stratification develops. The shallowness of the lake also prevents the occurrence of internal seiches. The response to changes in water quality is comparatively fast.

The lakes are further distinguished by their different freezing conditions. L. Vättern virtually never freezes, L. Vänern freezes on average every other year, whereas the absence of a winter ice cover on L. Mälaren and L. Hjälmaren is rare.

References

1. Wastenson, L. (ed.). 1995. *Climate, Lakes and Water-courses*. Sveriges Nationalatlas, Bokförlaget Bra Böcker, Höganäs. (In Swedish).
2. Herdendorf, C.E. 1990. Distribution of the world's large lakes. In*: Large Lakes. Ecological Structure and Function*. Tilzer, M.M. and Serruya, C. (eds). Springer-Verlag, Berlin.
3. Håkanson, L. and Ahl, T. 1976. Vättern – recent sediments and sediment chemistry. *Swedish Environmental Protection Agency, PM 740*. (In Swedish).
4. Håkanson, L. 1977. Sediments as indicators of contamination – Investigations in the four largest Swedish Lakes. *Swedish Environmental Protection Agency, PM 839*.
5. Håkanson, L. 1981. Lake sediments in aquatic pollution control programs; principles, processes and practical examples. *Swedish Environmental Protection Agency PM 1398*.
6. Håkanson, L. 1982. Bottom dynamics in lakes. *Hydrobiologia 91*, 9–22.
7. Håkanson, L. 1979. Lake Mälaren's islands – an inventory. *Swedish Environmental Protection Agency PM 1178*. (In Swedish).
8. Håkanson, L. 1978. Lake Hjälmaren – a physical description. *Swedish Environmental Protection Agency, PM 1079*. (In Swedish).
9. Gottschalk, L. 1978. Hydrology – water balance. In: *Lake Vänern, a Natural Resource*. Ahlgren, N., Knutsson, H. and Larsson, J.E. (eds). Swedish Environmental Protection Agency, Liber, pp. 29–38. (In Swedish).
10. Olsson, H. 1987. The phosphorus and nitrogen loading on Lake Hjälmaren 1966–1985. *Swedish Environmental Protection Agency, Report 3309*. (In Swedish).
11. Melin, R. 1970. *Nordic Hydrology*. Utbildningsförlaget, Stockholm. (In Swedish).
12. Dickson, W. 1986. Liming in Sweden. In: *Liming Acidic Waters: Environmental and Policy Concerns*. Conf. Proceedings, The Center for Environmental Information, New York, pp. 29–40.
13. ILEC/UNEP1987–1989. *Survey of the State of World Lakes*. Interim report 1+4 Lake Biwa Research Institute, Otsu, Japan.
14. Fager, P.-J. 1977. The damming of Lake Mälaren. *Mälaren's Water Protection Association, Västerås, Report no. 31.* (In Swedish).
15. Wallin, M (ed.). 2000. Lake Mälaren. The environmental status and development 1973–1994. *Mälaren's Water Protection Association, Västerås, Report*. (In Swedish).
16. Persson, G., Olsson, H. and Willén E. 1990. Water quality of Lake Mälaren during 20 years; 1. Nutrients: Input, in-lake concentrations and phytoplankton. *Swedish Environmental Protection Agency, Report 3759*. (In Swedish).
17. Wallin, M. and Persson, J. 1986. Nitrogen retention in Lake Vänern. Background data for decisions on nitrogen reduction at four municipial sewage-works*. Lake Vänern Society for Water Conservation, Report no 3*. (In Swedish).
18. Palmer, M.D. 1975. Coastal region residense time estimates from concentration gradients. *J. Great Lakes Res. 1*, 130–141.
19. Kvarnäs, H. 1978. Estimates of phosphorus concentration in subareas of lakes from concentration gradients of total dissolved solids. *Vatten 4*, 265–271.
20. Persson, J., Håkanson, L. and Pilesjö, P. 1994. Prediction of surface water turnover time in coastal waters using digital batymeric information. *Environmetrics 5*, 433–499.
21. Larsen, D.R. and Mercier, H.T. 1976. Phosphorus retention capacity of lakes. *J. Fish. Res. Board Can. 33*, 1742–1750.
22. Olsson, H. 1991. Nutrient balances for phosphorus and nitrogen in Lake Vänern 1970–89. *Vatten 47*, 263–272.
23. Halbfass, W. 1910. Gibt es im Madüsee Temperaturseiches? *Int. Rev. Hydrobiol. Hydrogr. 3*, 1–40.
24. Bergsten, F. 1926. *The Seiches of Lake Vetter*. Thesis, The Faculty of Sciences, Centraltryckeriet, Stockholm.
25. Pickett, R.L. and Richards, F.P. 1975. Lake Ontario mean temperature and currents in July 1972. *J. Phys. Oceanogr. 5*, 775–781.
26. Holmström, I. and Carlsson. B. 1978. The hydrodynamics of Lake Vänern. In: *Lake Vänern, a Natural Resource.* Ahlgren, N., Knutsson, H. and Larsson, J.E. (eds). Swedish Environmental Protection Agency, Liber, pp. 29–38. (In Swedish).
27. Kvarnäs, H. 1975. The geostrofic current of Lake Värmlandssjön (Lake Vänern). *Swedish Environmental Protection Agency, PM 561*. (In Swedish).
28. Kvarnäs, H. 1978 Dynamic studies in Lake Vänern and Lake Mälaren. *Swedish Environmental Protection Agency, PM 1030*. (In Swedish).
29. Simons, T.J., Funkquist, L. and Svensson, J. 1977. Application of a numerical model to lake Vänern. *Swedish Meteorological and Hydrological Institute, No RHO 9*, Norrköping.
30. Funkquist, L. 1979. The dynamics of lake Vättern, an introduction*. Swedish Meteorological and Hydrological Institute, No RHO 16*, Norrköping. (In Swedish).
31. Weyhenmeyer, G.A. 2001. Warmer winters – are planktonic algal populations in Sweden's largest lakes affected? *Ambio 30,* 565–571.
32. Ehlin, U. 1974. Dynamics of the water in the coastal zone – field and model studies. Ninth Nordic Symposium of Water Research, *Nordforsk, Miljövårdssekretariatet, Publ. 1974:4.* (In Swedish).

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